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Transmission congestion tracing technique and its application to recognize weak parts of bulk power systems

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Abstract A bulk power system is conventionally characterized by a complex structure with a large number of components. Each component generally has a different contribution to the transmission congestion (TC) of a system. Thus, a TC sharing method that can be used to evaluate the contribution of each component to the system TC and recognize the weak parts from the perspective of TC should be built. This paper presents a transmission congestion tracing (TCT) principle based on the failed component sharing principle and proportional sharing principle and a TCT model using the Monte Carlo simulation method. Case studies on the IEEE Reliability Test System indicate that the proposed method is effective and feasible.

Keywords Transmission congestion, Congestion indices, Congestion tracing principle, Component congestion contribution, Recognizing weak parts

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1 Introduction

A bulk power system (BPS) is generally characterized by a complex structure with a large number of components, such as generating units, transmission lines, and transformers. Each component exerts a different effect on the transmission congestion (TC) of a BPS. A functional TC sharing method can be used to quantify the contribution of each component to the TC of a BPS. Using this method, the key components that cause TC can be determined, and the weak parts of a BPS can be recognized. This method is also beneficial to optimize the type, number, and location of the flexible AC transmission system components, power system operations, and maintenance plans.

TC management is one of the major tasks performed by system operators to ensure that the operation of a transmission system is within operating limits [1]. Considerable work has been undertaken to develop TC models, TC elimination measures [2–5], TC benefit-cost analyses [6–11], and TC evaluation models and algorithms [12, 13].

Numerous studies have been conducted on power system reliability evaluation models and indices, such as the loss of load probability, loss of load expectation, and expected energy not supplied [14–17]. At present, the tracing technique has been applied to trace power flow [18–20], as well as in the unreliability of general complex networks, generation systems, and BPS [21–24]. The power tracing method allows the assessment of the contributions of individual generators (or loads) to individual line flows, which often utilize sensitivity analysis. This method can determine the relation between generator/load nodes and transmission lines in a power network and verify changes in the line flow along with the change in nodal generation/demand. Thus, the weak parts of a system can be recognized according to the change value [18–20]. For reliability tracing, the key components that cause unreliability are obtained according to reliability principles, that is, the failed component sharing principle (FCSP) and proportional sharing principle (PSP), and the reliability tracing results are the direct contribution of the weak parts to risks [21–24]. Both the sensitivity analysis and reliability tracing method can be used to recognize the key components that cause risk. Compared with sensitivity analysis, some of the advantages of the reliability tracing method are as follows.

1) Sensitivity analysis can test the effect of a component on risk in a system state. When several components fail simultaneously, the contribution of each failed component to risk cannot be estimated by sensitivity analysis. By contrast, the reliability tracing method can simultaneously analyze and estimate the contribution portion of multiple failed components to risk.

2) Sensitivity analysis repeatedly evaluates the contribution portion of every failed component to risk, whereas the reliability tracing method conducts only a one-time estimation to obtain the risk sharing indices and further improve the computational efficiency.

Considerable work has been conducted on the tracing techniques in power systems, including power flow tracing and unreliability tracing, and in the TC field, which is mainly focused on TC models, TC elimination measures, TC benefit-cost analysis, and TC evaluation. Unfortunately, no work has been conducted on the technique for tracing TC contributions and recognizing the weak parts of bulk power systems.

Considering the uncertainty of random failures of components, such as generating units, transmission lines, and transformers, a previous study [13] presented TC indices for the transmission components and overall system, which can be used to describe the TC degree. The present study utilizes a similar idea proposed in [21–24] to trace the TC indices suggested in [13]. Thus, this paper aims to recommend a recognition method for weak parts based on TC.

Notably, congestion under normal conditions frequently occurs because of heavy load growth without a good shedding load policy. In other words, a good shedding load policy can reduce and even eliminate the occurrence of congestion. Thus, only TC tracing (TCT) problems caused by failed components are discussed in this paper.

The paper proposes FCSP and PSP and establishes a TCT model and algorithm using the Monte Carlo technique. According to the TCT results, the weak system parts that cause TC can be recognized.

2 TC indices of power systems

The TC indices proposed in [13] are as follows. Among these indices, the first four are the indices for transmission components, and the rest are for power systems.

1) In a given time period, the occurrence probability of TC at transmission component i is

$$TLCP_i = \sum_{t \in D} P_t$$

where D is the system state set of TC occurring at the i^{th} transmission component; P_t is the probability of the t^{th} system state.

2) In a given time period, the TC frequency occurring at transmission component i is

$$TLCF_i = \sum_{t \in D} F_t = \sum_{t \in D} P_t \sum_{k=1}^{N} \lambda_k$$

where F_t is the occurrence frequency of the t^{th} system state; N is the number of components in a power system; λ_k is the transition rate of the k^{th} component in state D. If the k^{th} component is up, then λ_k is the failure rate; otherwise, λ_k is the repair rate.

3) In a given time period, the maximum congestion capacity of transmission component i is

$$TLCC_{i-\max} = \max_{t \in D}(TLCC_{it})$$

where $TLCC_{it}$ is the congestion capacity of transmission component i at the t^{th} state and $TLCC_{it} = C_{it} - C_{\text{rated}}$; C_{it} and C_{rated} are the actual capacity at the t^{th} state and the rated capacity of the i^{th} transmission component, respectively.

4) In a given time period (one year), the congestion energy of the i^{th} transmission component is

$$TLCE_i = \sum_{t \in D} TLCC_{it} \times TLCP_{it} \times 8760$$

where $TLCP_{it}$ is the probability of transmission component i at the t^{th} system state.

5) In a given time period, the occurrence probability of TC in a power system is

$$SCP = \sum_{t \in S} P_t$$

where S is the set of all the TC system states.

6) The system congestion frequency is given by

$$SCF = \sum_{t \in S} F_t = \sum_{t \in S} P_t \sum_{k=1}^{N} \lambda_k$$

7) The maximum system congestion capacity is

$$SCC_{\max} = \max_{t \in S}\left(\sum_{i=1}^{l} TLCC_{it}\right)$$

where l is the number of congested transmission components at the t^{th} system state.

8) The system congestion energy is given by

$$SCE = \sum_{t \in S} P_t \times SCC_t \times 8760$$

where SCC_t is the system congestion capacity at the t^{th} system state.

3 TCT principle

The above-cited study [13] proposed TC indices by considering the random failures of power components using the Monte Carlo technique. Assuming that a simulated system state occurs with a given SCP because of the simultaneous failure of three components, the questions that arise are as follows: How much is the "contribution" of a particular component to the SCP? What are the major TC contributions in a power system?

Two basic TCT principles are proposed for TCT in BPS.

1) FCSP

The obligation for a TC system state is assigned to the failed components. In other words, healthy components have no obligation for a TC system state. TC does not generally occur in a normal state. Thus, a TC index should be shared by the failed components for a TC system state.

2) PSP

The TC indices are proportionally shared among failed components.

According to the TCT principles described above, a proportional sharing method suitable for the Monte Carlo technique can be obtained.

Certain failed components notably exert no effect on a power system TC; thus, they do not share in the TC responsibility. Failed transmission components should generally share the TC responsibility directly because of their effect on TC, and these effective failed components contribute to TC. However, certain generating units possibly exert no effect on TC. Thus, the generating units that are responsible for TC should be filtered from the failed generating units. A combination of the Monte Carlo and enumeration methods is used to filter the failed generating units in this paper. The algorithm can be summarized in the following steps.

Step 1 Assume that v components in a system fail simultaneously, and TC occurs (e is a system congestion index A). "U" failed generating units among all the failed components are denoted as $q_1, q_2, \ldots, q_u$.

Step 2 Let the i^{th} failed generating unit q_i recover a healthy component from a failed component, and calculate the TC index A as f.

Step 3 If $f = e$, then the generating unit q_i exerts no effect on TC, so that the generating unit is a non-effective failed component that does not contribute to TC. If $f < e$, then the generating unit exerts an effect on TC, so that the generating unit is an effective failed component that contributes to TC.

Step 4 Repeat Steps 2 and 3 until all the failed generating units are enumerated. The effective failed generating units, which should share TC responsibility, are filtered in this manner.

Evidently, the failed components for FCSP and PSP are effective failed components.

We assume that t is a TC system state simulated by the Monte Carlo technique because of the simultaneous failure of m effective failed components. Let φ_t be a TC index of system state t.

In a system state simulated by the Monte Carlo technique, each effective failed component possesses an equal obligation for a failure system state based on PSP. Thus, each effective failed component j among m effective failed components should be assigned $1/m$ contribution to the TC index φ_t, which is given by

$$\varphi(t \to j) = \frac{1}{m}\varphi_t \quad j = 1, 2, \cdots, m \tag{1}$$

As shown in (1), PSP possesses an identity. In other words, TC indices can be shared equally and completely.

4 Tracing TC indices for BPS

We assume that a BPS has N components and each component presents only two states: up and down. Using the TCT principle, TCT models can be obtained for the transmission components and the system.

4.1 Tracing models for TC indices of transmission component

1) Tracing model for TC index $TLCP_i$

According to the PSP described above, the $TLCP_i$ index tracing model for the effective failed component j is given by

$$TLCP_i(D \to j) = \sum_{t \in D} \frac{P_t}{m_t} \tag{2}$$

where m_t is the number of effective failed components in the t^{th} TC state t.

2) Tracing model for index $TLCF_i$

The $TLCF_i$ index sharing model for the effective failed component j is given by

$$TLCF_i(D \to j) = \sum_{t \in D} \frac{F_t}{m_t} \tag{3}$$

3) Tracing model for indices $TLCC_{i\text{-max}}$ and $TLCE_i$

Similarly, the $TLCC_{i\text{-max}}$ and $TLCE_i$ sharing models for the effective failed component j are given by

$$TLCC_{i-\max}(D \to j) = \frac{TLCC_{i-\max}}{m_t} \tag{4}$$

$$TLCE_i(D \to j) = \sum_{t \in D} \frac{P_t}{m_t} \times TLCC_{it} \times 8760 \tag{5}$$

4.2 Tracing models for system TC indices

1) Tracing model for index SCP

The SCP tracing model for the effective failed component j is given by

$$SCP(S \to j) = \sum_{t \in S} \frac{P_t}{m_t} \tag{6}$$

2) Tracing model for index SCF

The SCF tracing model for the effective failed component j is given by

$$SCF(S \to j) = \sum_{t \in S} \frac{F_t}{m_t} \tag{7}$$

3) Tracing model for index $SCC_{\max}$ and SCE

Similarly, the $SCC_{\max}$ and SCE tracing models for the effective failed component j are given by

$$SCC_{\max}(S \to j) = \frac{SCC_{\max}}{m_t} \tag{8}$$

$$SCE(S \to j) = \sum_{t \in S} \frac{P_t}{m_t} \times SCC_t \times 8760 \tag{9}$$

The TCT sharing factor (TCTSF) can be used to describe the degree of TC contribution per unit.

The TCTSF based on the $TLCP_i$ for the effective failed component j is given by $TCTSF_{Pi} = TLCP_i(D \to j)/TLCP_i$. The other indices can also be defined in the same manner.

For a given component, a greater magnitude of the TCTSF translates to a greater significance of the TC effect of the component on the system. The components with large *TCTSF* are the weak system parts.

Table 1 provides the TCTSF indices and calculation models of the effective failed component j.

Table 1 TCTSF indices and models of effective failed component j

Denotation	Calculation formula
$TCTSF_{Pi}$	$TLCP_i(D\to j)/TLCP_i$
$TCTSF_{Fi}$	$TLCF_i(D\to j)/TLCF_i$
$TCTSF_{Ci\text{-max}}$	$TLCC_{i\text{-max}}(D\to j)/TLCC_{i\text{-max}}$
$TCTSF_{Ei}$	$TLCE_i\ (D\to j)/TLCE_i$
$TCTSF_P$	$SCP(S\to j)/SCP$
$TCTSF_F$	$SCF(S\to j)/SCF$
$TCTSF_{C\max}$	$SCC_{\max}(S\to j)/SCC_{\max}$
$TCTSF_E$	$SCE(S\to j)/SCE$

5 TC tracing algorithm for BPS

A TCT algorithm for BPS can be summarized as follows.

Step 1 Calculate the TC indices for the transmission components $TLCP_i$, $TLCF_i$, $TLCC_{i\text{-max}}$ and $TLCE_i$, as well as the system TC indices SCP, SCF, $SCC_{\max}$ and SCE [13].

Step 2 Calculate the contribution of the effective failed component j to the transmission component and system indices using (2) to (5) and (6) to (9), respectively.

Step 3 Repeat Step 2 and calculate the contribution of each TC index of the other effective failed components.

Step 4 According to the indices and models in Table 1, calculate the TCTSF indices and identify the weak parts of a BPS.

6 Case studies

Case studies on the IEEE reliability test system (IEEE-RTS) are used to verify the effectiveness of the proposed model. Figure 1 shows a single line diagram of IEEE-RTS. The system includes 24 buses, 33 AC transmission lines, 5 transformers, and 32 generating units. The total generation capacity is 3405 MW and the peak load is 2850 MW. The relevant electrical and reliability parameters of the components are shown in [25]. A constant load, that is, the peak load, and load curtailment philosophy, such as Pass-I Policy and Average Policy [13], are used in the proposed TCT models. The non-sequential Monte Carlo technique with 1 million simulation replications is used to analyze the system. After a random sampling of the state of the generating units, transmission lines, and transformers, the power deviation between the total generation and load demands can be calculated. If the power deviation is negative, then the load is shed. Otherwise, the generating units are re-dispatched, and the system power flow is calculated. The results of the power flow are used to identify whether or not the transmission components are congested.

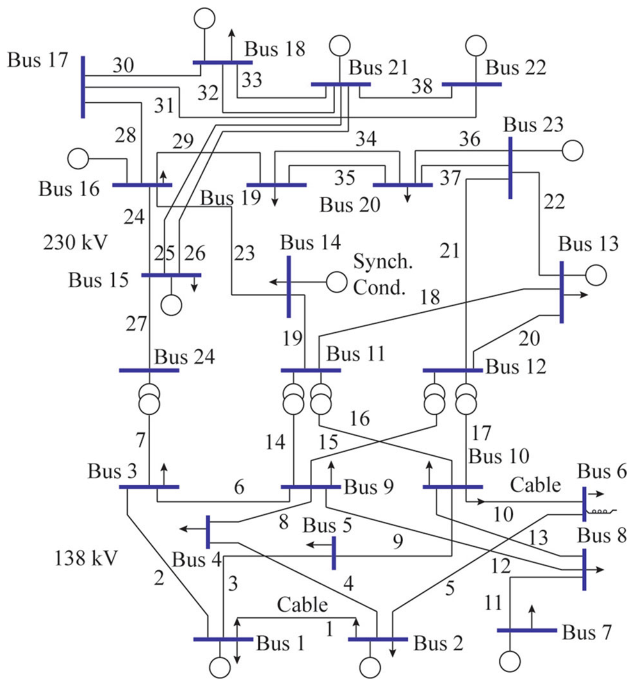

Fig. 1 Single line diagram of IEEE-RTS

The simulation program was coded using MATLAB 7.3 based on the proposed techniques and was run on a computer with a 2.4 GHz Intel Core i5-6200U CPU and 4 GB RAM. The computation time of 1 million simulations of the base case (Pass-I Policy) is 4.8 hours.

6.1 TCT and recognizing weak parts on Pass-I Policy

Based on [13], a constant load or peak load and Pass-I Policy are used in this analysis. Eight transmission components are congested because of the random failure of components. Table 2 shows the TC indices for these transmission components and system. L6 presents the most severe TC which has the largest TC indices.

6.1.1 *TCT for transmission components and system*

Tables 3 and 4 show the TCT and TCTSF indices associated with the TC of L6 and the system, respectively.

6.1.2 *TCT analysis of transmission components and system*

Tables 3 and 4 show that the sum of every TCTSF index for the components is 100%, including $TCTSF_{Pi}$, $TCTSF_{Fi}$ and $TCTSF_{Ei}$ for the component, $TCTSF_P$, $TCTSF_F$,

Table 2 TC indices for transmission components and system (constant load model, Pass-I Policy)

Transmission components	$TLCP_i$	$TLCF_i$ (times/year)	$TLCC_{i\text{-max}}$ (MVA)	$TLCE_i$ (MWh/year)
L6	4.0×10^{-6}	0.0081	168.17	2.24
L7	2.0×10^{-6}	0.0037	210.00	1.98
L13	3.0×10^{-6}	0.0048	12.92	0.34
L24	1.0×10^{-6}	0.0011	42.95	0.38
L25	1.0×10^{-6}	0.0025	162.67	1.43
L27	1.0×10^{-6}	0.0019	120.00	1.05
L28	1.0×0^{-6}	0.0011	57.59	0.50
L29	1.0×10^{-6}	0.0014	92.12	0.81

Note: System indices $SCP = 1.1 \times 10^{-5}$, $SCF = 0.0189$ times/year, $SCC_{\max} = 498.17$ MVA, $SCE = 8.72$ MWh/year

Table 3 TCT and TCTSF indices associated with TC of L6 (constant load model, Pass-I Policy)

Component	TCT indices for L6			TCTSF		
	$TLCP_i$	$TLCF_i$ (times/year)	$TLCE_i$ (MWh/year)	$TCTSF_{Pi}$ (%)	$TCTSF_{Fi}$ (%)	$TCTSF_{Ei}$ (%)
L2	1.00×10^{-6}	0.00165	0.225	25.00	20.40	10.06
L19	5.00×10^{-7}	0.00120	0.159	12.50	14.80	7.08
L23	5.00×10^{-7}	0.00120	0.737	12.50	14.80	32.86
L27	1.00×10^{-6}	0.00165	0.225	25.00	20.40	10.06
L29	1.00×10^{-6}	0.00240	0.895	25.00	29.60	39.94
All transmission components				100	100	100
All generating units				0	0	0
Total	4×10^{-6}	0.0081	2.24	100	100	100

$TCTSF_{C\max}$ and $TCTSF_E$ for the system. In other words, the TC indices for a BPS can be completely distributed among all the components using the proposed TCT technique.

Table 3 shows that the TC of L6 is caused by the failures of the transmission components based on 1 million simulation samplings and Pass-I Policy, which all account for 100% of the indices $TCTSF_{Pi}$, $TCTSF_{Fi}$ and $TCTSF_{Ei}$. Among the transmission components, L23 and L29 exert the greatest effect on the TC of L6, which accounts for 32.86% and 39.94% of the index $TCTSF_{Ei}$, respectively. The two transmission components account for 37.50%, 44.40% and 72.80% of $TCTSF_{Pi}$, $TCTSF_{Fi}$ and $TCTSF_{Ei}$, respectively. Thus, these two components are the weak parts that cause the TC of L6, which is due to the occurrence of TC at L6 when L23 and L29 are simultaneously in a down state. Under this state, L6 presents the greatest congestion capacity among all its TC states.

Table 4 shows that the transmission components L2, L7, L12, L23, L27, L28 and L29 exert a relatively large effect on the indices SCP and SCF. These seven components account for 68.18% and 67.51% of the indices $TCTSF_P$ and $TCTSF_F$. However, L2, L12 and L27 possess relatively larger $TCTSF_P$ and $TCTSF_F$ and a smaller $TCTSF_E$, which is due to the fact that the TC of these transmission components only occurs in the case of the failure of two and more component, and presents a smaller congestion capacity during each TC state.

Figure 2 shows the TCTSF indices of the system TCT based on Pass-I Policy. Figure 1 shows that L23 and L29 have a significant effect on the index SCE, which accounts for 57.68% of the index $TCTSF_E$. For the indices SCP, SCF, and SCE, the following seven components are the weak parts from the perspective of TC: L2, L7, L12, L23, L27, L28 and L29.

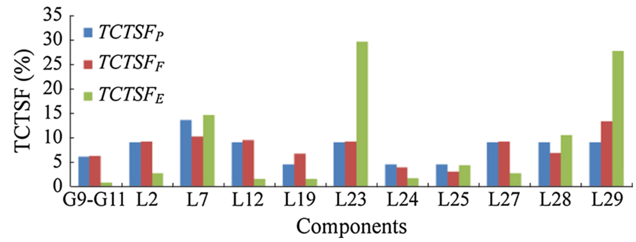

Fig. 2 System TCTSF (constant load model, Pass-I Policy)

Figure 2 shows that the major components that cause TC are the transmission components when using Pass-I Policy.

6.2 TCT and recognizing weak parts on Average Policy

Based on [13], the system TC occurs at eight transmission components because of the random failure of components while using Average Policy. Table 5 shows the TC indices for the eight congested transmission components and system. L11 shows the most severe TC because its TC indices are the largest.

Table 5 shows that the other seven congested transmission components exhibit a lower occurrence probability of TC than L11, whereas their TC capacity is relatively

Table 4 TCT and TCTSF indices associated with TC of system (constant load model, Pass-I Policy)

Component	Capacity (MW)/Bus	System TCT indices				TCTSF			
		SCP	SCF (times/year)	$SCC_{\max}$ (MVA)	SCE (MWh/year)	$TCTSF_P$ (%)	$TCTSF_F$ (%)	$TCTSF_{C\max}$ (%)	$TCTSF_E$ (%)
G9, G10, G11	100/Bus7	6.67×10^{-7}	0.00120	0	0.075	6.06	6.33	0	0.86
All generating units						18.17	18.97	0	2.61
L2		1.00×10^{-6}	0.00174	0	0.243	9.09	9.18	0	2.78
L7		1.50×10^{-6}	0.00194	0	1.283	13.64	10.24	0	14.71
L12		1.00×10^{-6}	0.00180	0	0.129	9.09	9.49	0	1.48
L19		5.00×10^{-7}	0.00126	0	0.132	4.55	6.66	0	1.51
L23		1.00×10^{-6}	0.00174	249.09	2.603	9.09	9.23	50	29.84
L24		5.00×10^{-7}	0.00073	0	0.143	4.55	3.84	0	1.64
L25		5.00×10^{-7}	0.00057	0	0.374	4.55	3.02	0	4.28
L27		1.00×10^{-6}	0.00174	0	0.243	9.09	9.18	0	2.78
L28		1.00×10^{-6}	0.00130	0	0.918	9.09	6.86	0	10.53
L29		1.00×10^{-6}	0.00252	249.09	2.428	9.09	13.33	50	27.84
All transmission components						81.83	81.03	100	97.39
Total		1.1×10^{-5}	0.018 9	498.17	8.72	100	100	100	100

Table 5 TC indices for transmission components (constant load model, Average Policy)

Transmission components	$TLCP_i$	$TLCF_i$ (times/year)	$TLCE_i$ (MWh/year)
L11	2.6×10^{-4}	0.2308	7.17
L6	4.0×10^{-6}	0.0081	2.24
L7	2.0×10^{-6}	0.0037	1.98
L13	3.0×10^{-6}	0.0048	0.34
L25	1.0×10^{-6}	0.0025	1.43
L27	1.0×10^{-6}	0.0019	1.05
L28	1.0×10^{-6}	0.0011	0.50
L29	1.0×10^{-6}	0.0014	0.81

Note: System indices $SCP = 2.72 \times 10^{-4}$, $SCF = 0.2500$ times/year, $SCE = 15.56$ MWh/year

Table 6 TCT and TCTSF indices associated with TC of L11 (constant load model, Average Policy)

Component	Capacity (MW)/Bus	TCT indices for L11			TCTSF		
		$TLCP_i$	$TLCF_i$ (times/year)	$TLCE_i$ (MWh/year)	$TCTSF_{Pi}$ (%)	$TCTSF_{Fi}$ (%)	$TCTSF_{Ei}$ (%)
G9, G10, G11	100/Bus7	1.81×10^{-5}	0.01595	0.586	6.95	6.9	8.18
G12, G13, G14	197/Bus13	7.22×10^{-6}	0.00721	0.172	2.78	3.1	2.39
G20	155/Bus15	6.31×10^{-6}	0.00652	0.213	2.43	2.8	2.97
G21	155/Bus16	5.87×10^{-5}	0.05051	1.520	22.57	21.89	21.21
G22	400/Bus18	5.91×10^{-5}	0.05075	1.520	22.73	21.99	21.20
G23	400/Bus21	8.36×10^{-6}	0.00858	0.240	3.21	3.72	3.34
G30, G31	155/Bus23	5.56×10^{-5}	0.04730	1.456	21.38	20.50	20.31
G32	350/Bus23	1.81×10^{-5}	0.01595	0.586	6.95	6.91	8.18
All generating units					99.17	98.48	99.30
L28	–	9.75×10^{-7}	0.00182	0.034	0.38	0.79	0.48
L33	–	1.95×10^{-7}	0.00031	0.001	0.08	0.14	0.02
L35	–	9.75×10^{-7}	0.00137	0.015	0.38	0.60	0.21
All transmission components					0.83	1.52	0.70
Total		2.60×10^{-4}	0.23080	7.170	100	100	100

large. Thus, the transmission components exert a comparatively large effect on *SCE*.

6.2.1 *TCT for transmission components and system*

Tables 6 and 7 show the TCT and TCTSF indices associated with the TC of L11 and the system, respectively. The TC indices for a BPS can also be completely distributed among all the components.

6.2.2 *TCT analysis of transmission components and system*

Figure 3 shows the TCTSF indices of the system TCT using Average Policy, with G22, G23 and G32 exerting the greatest effect on the indices *SCP* and *SCF*. These three components account for 64.03% and 59.52% of indices $TCTSF_P$ and $TCTSF_F$. A similar conclusion can be drawn using Pass-I Policy. The transmission components L23 and L29 have a significant effect on the index *SCE*, which accounts for 30.97% of index $TCTSF_E$. For Pass-I Policy, when the BPS encounters a severe contingency that requires load curtailment, the loads are curtailed at the buses that are closest to the elements on outage. For Average Policy, when the BPS encounters a severe contingency that requires load curtailment, all the loads at the buses are curtailed with a similar proportion. For IEEE-RTS, G22, G23 and G32 present the largest or second largest equivalent unavailable capacity (generation capacity × unavailability) among all the generating units. If the total capacity of the generating units is less than the load

Table 7 TCT and TCTSF indices associated with TC of system (constant load model, Average Policy)

Component	Capacity (MW)/Bus	System TCT indices				TCTSF			
		SCP	*SCF* (times/year)	$SCC_{\max}$ (MVA)	*SCE* (MWh/year)	$TCTSF_P$ (%)	$TCTSF_F$ (%)	$TCTSF_{C\max}$ (%)	$TCTSF_E$ (%)
G9 G10 G11	100/Bus7	6.55×10^{-7}	0.00109	0	0.072	0.24	0.44	0	0.46
G12 G13 G14	197/Bus13	1.82×10^{-5}	0.01597	0	0.585	6.68	6.39	0	3.76
G20	155/Bus15	7.25×10^{-6}	0.00722	0	0.171	2.67	2.89	0	1.10
G21	155/Bus16	6.34×10^{-6}	0.00653	0	0.213	2.33	2.61	0	1.37
G22	400/Bus18	5.90×10^{-5}	0.05060	0	1.516	21.68	20.24	0	9.74
G23	400/Bus21	5.94×10^{-5}	0.05084	0	1.516	21.82	20.33	0	9.74
G30 G31	155/Bus23	8.40×10^{-6}	0.00860	0	0.239	3.09	3.44	0	1.54
G32	350/Bus23	5.58×10^{-5}	0.04739	0	1.452	20.53	18.95	0	9.33
All generating units						95.95	92.38	0	47.01
L2		9.83×10^{-7}	0.00215	0	0.217	0.36	0.86	0	1.40
L7		1.48×10^{-7}	0.00175	0	0.814	0.54	0.70	0	5.23
L12		9.83×10^{-7}	0.00163	0	0.108	0.36	0.65	0	0.69
L19		4.92×10^{-7}	0.00091	0	0.221	0.18	0.36	0	1.42
L23		9.83×10^{-7}	0.00161	249.09	2.494	0.36	0.64	50	16.03
L24		4.92×10^{-7}	0.00052	0	0.243	0.18	0.21	0	1.56
L25		4.92×10^{-7}	0.00123	0	0.687	0.18	0.49	0	4.42
L27		9.83×10^{-7}	0.00215	0	0.217	0.36	0.86	0	1.40
L28		1.97×10^{-7}	0.00358	0	0.903	0.72	1.43	0	5.80
L29		9.83×10^{-7}	0.00182	249.09	2.325	0.36	0.73	50	14.94
L33		1.97×10^{-7}	0.00031	0	0.001	0.07	0.13	0	0.01
L35		9.83×10^{-7}	0.00138	0	0.015	0.36	0.55	0	0.09
All transmission components						4.05	7.62	0	52.99
Total		2.72×10^{-4}	0.2500	498.17	15.56	100	100	100	100

Note: To highlight the key components, components with a TC contribution of less than 2% are not shown in the table

demands, then the loads must be shed to keep the system in a normal state. Thus, these three components present a larger probability to cause load shedding in their down states than the other generating units. Based on Pass-I Policy, the loads at Bus 7 and Bus 8 should not be shed because of their far distance from the elements on outage. Based on Average Policy, the loads at Bus 7 and Bus 8 should be shed with the same proportion as that of the other loads used. Considering that the output of the generating units at Bus 7 remains unchanged, as well as its load curtailment, the power flow of L11 increases, which may lead to the occurrence of TC at L11. Thus, L11 shows the largest $TLCP_i$ and $TLCF_i$ among all the transmission components in the BPS, and its $TLCP_i$ or $TLCF_i$ is larger than the sum of the other seven transmission components. Evidently, *SCP* and *SCF* mainly depend on the $TLCP_i$ and $TLCF_i$ of L11.

Based on *SCP*, *SCF* and *SCE*, the weak parts that cause TC are G22, G23, G32, L23 and L29.

Figure 3 shows that the major components that cause TC are the generating units, as well as L23 and L29, using Average Policy. The failures of the generating unit have less effect on TC when using Pass-I Policy load curtailment philosophy than when using Average Policy.

The proposed TCT models can be used to distribute impartially and reasonably the TC indices to each effective failed component. According to the TCT results, the weak parts that cause TC can be recognized.

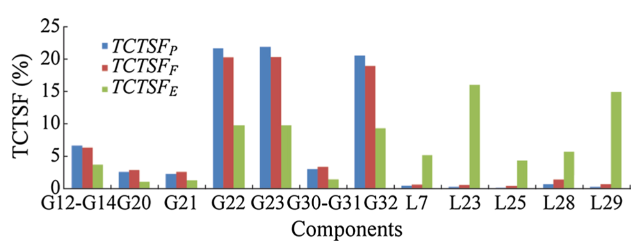

Fig. 3 System TCTSF (constant load model, Average Policy)

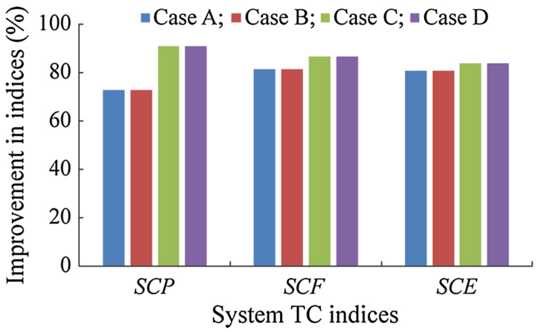

Fig. 4 Comparison of system TC indices of Cases A, B, C and D

6.3 Comparison of improvement measures

A constant load and Pass-I load curtailment policy are used in this section. Based on the analysis in Section 6.1, seven components are the weak parts from the perspective of TC. The transmission component L7 has the largest $TCTSF_P$ and a relatively larger $TCTSF_F$ and $TCTSF_E$ than the other components, whereas the transmission component L28 has the smallest $TCTSF_P$. Thus, four cases are analyzed.

Case A the failure rate of L7 is reduced by 50%.
Case B the repair time of L7 is decreased by 50%.
Case C the failure rate of L28 is lessened by 50%.
Case D the repair time of L28 is diminished by 50%.

Figure 4 shows the *SCP*, *SCF* and *SCE* indices for the BPS when the reliability performance of L7 and L28 are changed. The system *SCP* is 9×10^{-6} in Case A, which represents a drop of 9.09% compared with the *SCP* in Case C and a drop of 18.19% compared with the *SCP* in the base case. Similar conclusions can be drawn for the *SCF* and *SCE* indices of Cases A and C and for the indices of Cases B and D. These results indicate that, compared with L28, L7 is a weak part from the perspective of TC.

7 Conclusion

This paper presents TCT principles—FCSP and PSP, and builds TCT models using a similar idea employed in reliability tracing.

TCT models can be used to distribute the contribution of each component to TC indices and obtain the TCT indices of the transmission components and system, which can be used to recognize the weak parts of a power system that cause TC. The correctness and efficiency of the proposed TCT models are verified by case studies on IEEE-RTS. The proposed techniques are actually general methods for tracing TC without any special assumptions or requirements associated with power systems and can be extended to trace the TC of power systems containing wind power.

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